FOM-Institute for Plasma Physics Rijnhuizen
Association Euratom-FOM

On the Merits of Heating and Current Drive for Tearing Modes Stabilization

D. De Lazzari, E. Westerhof

US-Japan Workshop on MHD Control, Magnetic Islands and Rotation

Outline

- ECCD or ECRH? A brief introduction to the topic
  - The framework: MRE, assumption and limits
  - Electron Cyclotron Current Drive;
  - Electron Cyclotron Resonance Heating;
- ECCD VS ECRH:
  - Fore factor;
  - Geometrical efficiency;
  - Application of the model to ITER, AUG and TEXTOR;
- Conclusions and Outlooks

Outline

- ECCD or ECRH? A brief introduction to the topic
  - The framework: MRE, assumption and limits
  - Electron Cyclotron Current Drive;
  - Electron Cyclotron Resonance Heating;
- ECCD VS ECRH:
  - Fore factor;
  - Geometrical efficiency;
  - Application of the model to ITER, AUG and TEXTOR;
- Conclusions and Outlooks

Outline

- ECCD or ECRH? A brief introduction to the topic
  - The framework: MRE, assumption and limits
  - Electron Cyclotron Current Drive;
  - Electron Cyclotron Resonance Heating;

- ECCD VS ECRH:
  - Fore factor;
  - Geometrical efficiency;
  - Application of the model to ITER, AUG and TEXTOR;

- Conclusions and Outlooks

ECCD or ECRH?

- ECCD and ECRH are proven to stabilize NTMs.

- ECRH is proven experimentally to be the dominant effect for island suppression in TEXTOR and T-10;

- Experiments on middle-large size tokamaks (DIII-D, JT-60, ASDEX) showed the same effect to be negligible compared to ECCD;

- In AUG a previous theoretical model (Yu, PPCF. 40, 1998) estimated ECRH to be more effective than ECCD; Experiments so far haven't provided yet a clear confirmation;

- Predictions for NTMs stabilization in ITER are currently not including the ECRH contribution.
  - More theoretical work to assess the validity of this approach is needed!

ECCD or ECRH?

- ECCD and ECRH are proven to stabilize NTMs.
- ECRH is proven experimentally to be the dominant effect for island suppression in TEXTOR and T-10;
- Experiments on middle-large size tokamaks (DIII-D, JT-60, ASDEX) showed the same effect to be negligible compared to ECCD;
- In AUG a previous theoretical model (Yu, PPCF. 40, 1998) estimated ECRH to be more effective than ECCD; Experiments so far haven't provided yet a clear confirmation;
- Predictions for NTMs stabilization in ITER are currently not including the ECRH contribution.
  - More theoretical work to assess the validity of this approach is needed!

ECCD or ECRH?

- ECCD and ECRH are proven to stabilize NTMs.
- ECRH is proven experimentally to be the dominant effect for island suppression in TEXTOR and T-10;
- Experiments on middle-large size tokamaks (DIII-D, JT-60, ASDEX) showed the same effect to be negligible compared to ECCD;
- In AUG a previous theoretical model (Yu, PPCF. 40, 1998) estimated ECRH to be more effective than ECCD; Experiments so far haven't provided yet a clear confirmation;
- Predictions for NTMs stabilization in ITER are currently not including the ECRH contribution.
  - More theoretical work to assess the validity of this approach is needed!

ECCD or ECRH?

- ECCD and ECRH are proven to stabilize NTMs.
- ECRH is proven experimentally to be the dominant effect for island suppression in TEXTOR and T-10;
- Experiments on middle-large size tokamaks (DIII-D, JT-60, ASDEX) showed the same effect to be negligible compared to ECCD;
- In AUG a previous theoretical model (Yu, PPCF. 40, 1998) estimated ECRH to be more effective than ECCD; Experiments so far haven't provided yet a clear confirmation;
- Predictions for NTMs stabilization in ITER are currently not including the ECRH contribution.
  - More theoretical work to assess the validity of this approach is needed!

JÜLICH FORSCHUNGSZENTRUM

ECCD or ECRH?

- ECCD and ECRH are proven to stabilize NTMs.
- ECRH is proven experimentally to be the dominant effect for island suppression in TEXTOR and T-10;
- Experiments on middle-large size tokamaks (DIII-D, JT-60, ASDEX) showed the same effect to be negligible compared to ECCD;
- In AUG a previous theoretical model (Yu, PPCF. 40, 1998) estimated ECRH to be more effective than ECCD; Experiments so far haven't provided yet a clear confirmation;
- Predictions for NTMs stabilization in ITER are currently not including the ECRH contribution.
  - More theoretical work to assess the validity of this approach is needed!

The model: assumption and limits

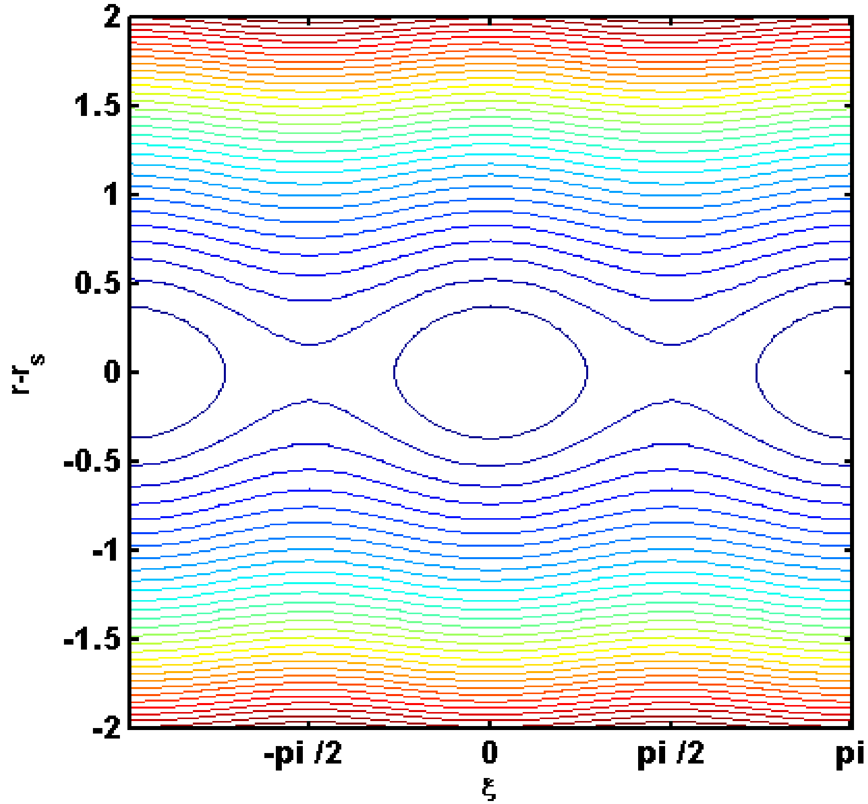
- Large aspect ratio;
- Constant Ψ approximation;

$$0.82 \cdot \frac{\tau}{r_s}\frac{dw}{dt} = r_s\Delta' - r_s\Delta'_{\delta j}(w)$$

$$r_s\Delta_{\delta j} = \frac{2\mu_0 R}{Cw^2}\int_{-\infty}^{+\infty} dx r_S \oint d\xi (j_{//,1} + j_{//,2} + \ldots)\cos(m\xi);$$

$$r_s\Delta'_H = \frac{2\mu_0 R}{Cw^2}\int_{-\infty}^{+\infty} dx r_s \oint d\xi \frac{J_{sep}}{T_{sep}^{3/2}} T_e^{3/2}\cos(m\xi)$$

$$r_s\Delta'_{CD} = \frac{2\mu_0 R}{Cw^2}\int_{-\infty}^{+\infty} dx r_s \oint d\xi\, j_{CD}\cos(m\xi)$$



The model: assumption and limits

Assuming a Gaussian distribution for the power deposition profile, with $w_{dep} \sim w_{CD}$ and $r_{dep} \sim r_{cd}$:

$$r_s \Delta'_{H,CD} = \frac{32 \mu_0 r_s}{B_p s} \frac{P \eta_{H,CD}}{w_{dep}^2} F_{H,CD}(w^*, r_s - r_{dep}, D)$$

IF:

- The effect of misalignment depends weakly on $w^* = w/w_{dep}$;
- The effect of modulation does not depend on $r_s - r_{dep}$;

The geometrical efficiency can be factorized into three figures of merit:

$$F_{H,CD} \approx N_{H,CD}\left(w^*, r_{dep} = r_s\right) G_{H,CD}\left(w^*, r_s - r_{dep}\right) M_{H,CD}(w^*, D)$$

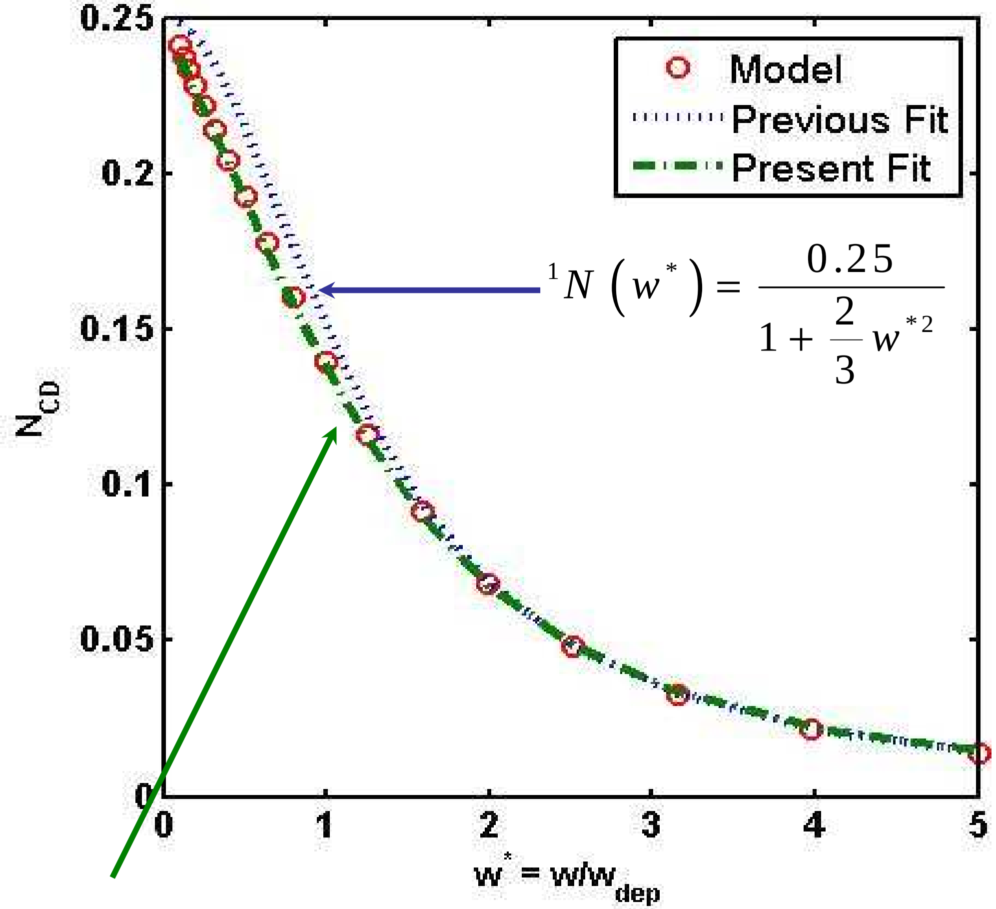
with: $M_{H,CD}(w^*, D=1) = 1$ $\quad G_{H,CD}(w^*, r_s = r_{dep}) = 1$

ECCD: Benchmark with Literature:

$$r_s \Delta'_{CD} = \frac{32\mu_0 r_s}{B_p s} \frac{P\eta_{CD}}{w_{dep}^2} N_{CD} G_{CD} M_{CD}$$

- Normalization function has been benchmarked with previous work (Sauter, Phys. Plasmas, 2004);

- A good agreement with the model is observed. A further improvement of the original function has been proposed in the picture.

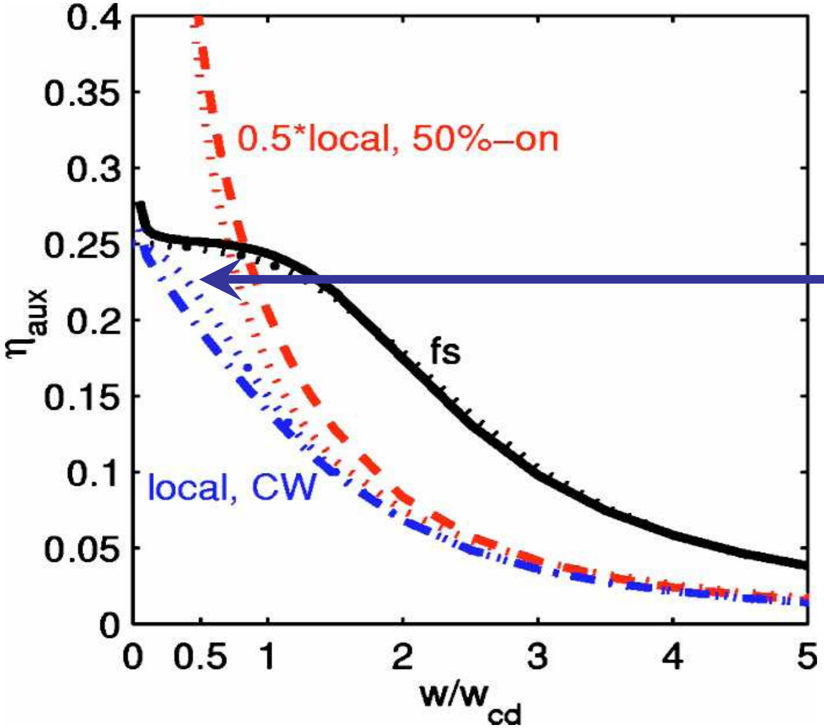


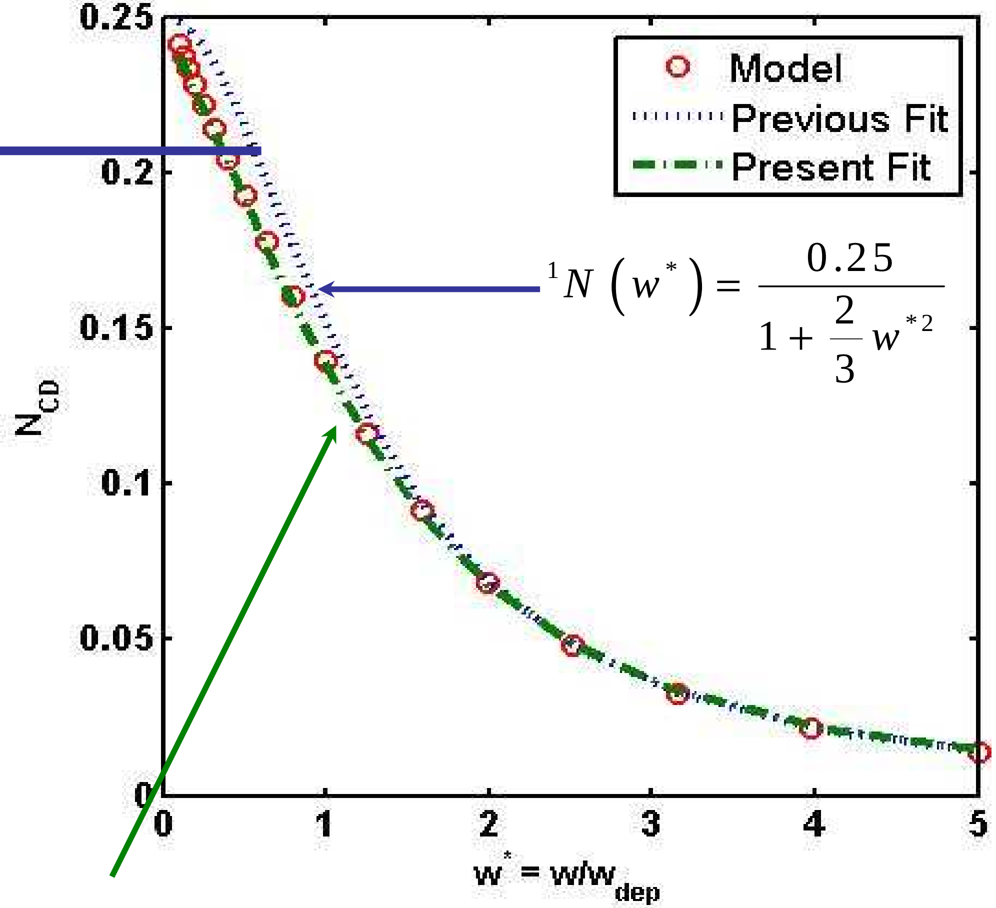
$$^1N\left(w^*\right) = \frac{0.25}{1 + \frac{2}{3} w^{*2}}$$

$$N\left(w^*\right) = \frac{0.25 + 0.24 w^*}{1 + 0.64 w^{*3} + 0.43 w^{*2} + 1.5 w^*}$$

ECCD: Benchmark with Literature:

$$r_s\Delta'_{CD} = \frac{32\mu_0 r_s}{B_p s}\frac{P\eta_{CD}}{w_{dep}^2} N_{CD} G_{CD} M_{CD}$$





$${}^1N\left(w^*\right) = \frac{0.25}{1+\frac{2}{3}w^{*2}}$$

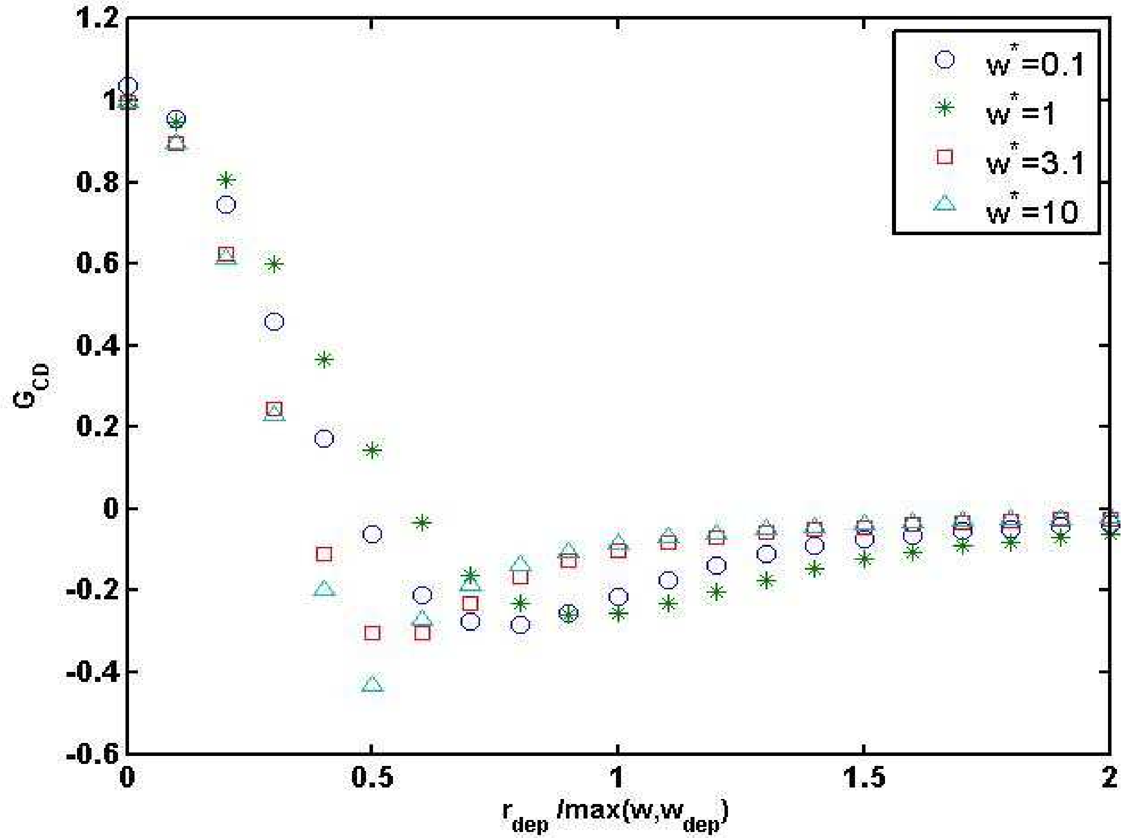
$$N\left(w^*\right) = \frac{0.25+0.24w^*}{1+0.64w^{*3}+0.43w^{*2}+1.5w^*}$$

- A good agreement with the model is observed. A further improvement of the original function has been proposed in the picture.

ECCD: Deposition location

- Around the separatrix ECCD is destabilizing the island;
- For "large" islands destabilization can reach the 50% of the $G_{CD}(r_s)$;
- At r_N=0.3, G_{CD} is reduced by ~60%;
- For "small" islands the trend is ~ the real part of the plasma dispersion function.

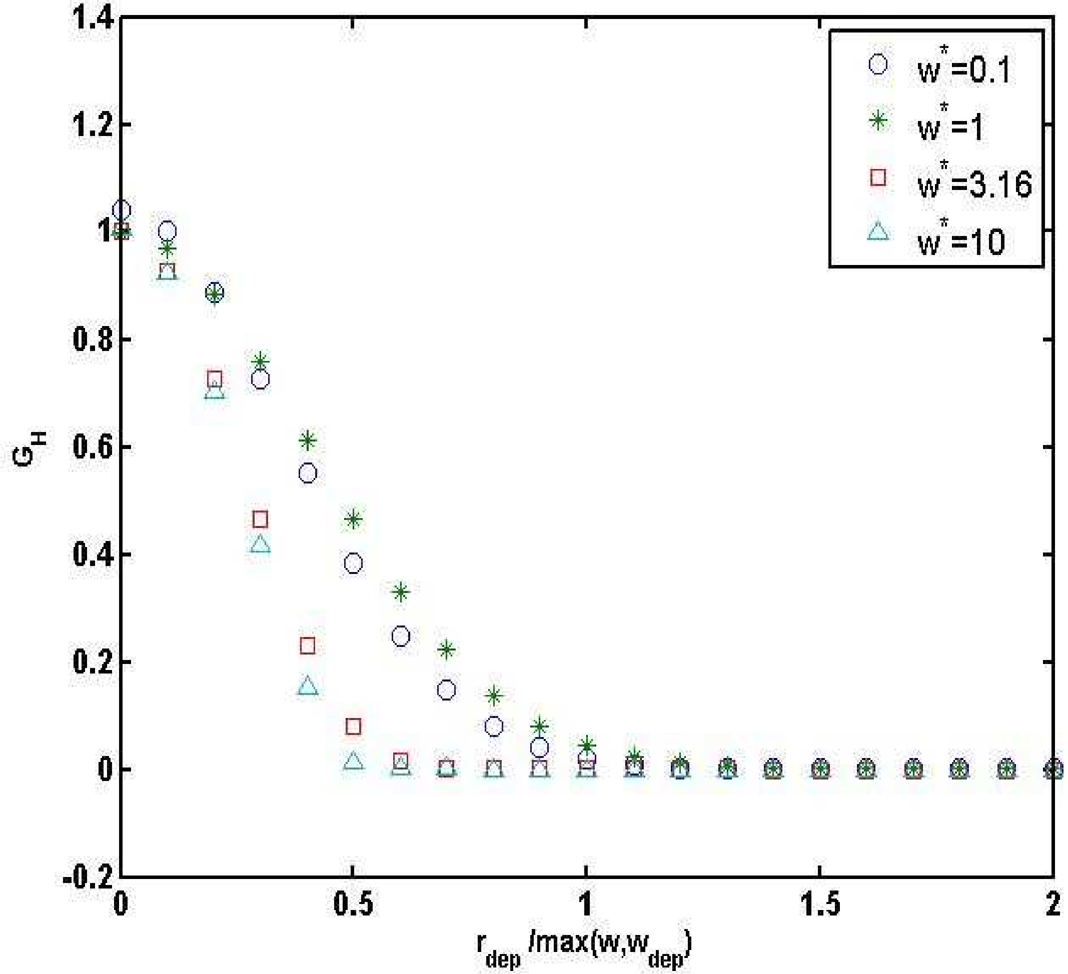
$$r_s \Delta'_{CD} = \frac{32\mu_0 r_s}{B_p s} \frac{P\eta_{CD}}{w_{dep}^2} N_{CD} G_{CD} M_{CD}$$



ECRH: Deposition location

$$r_s \Delta'_H = \frac{32\mu_0 r_s}{B_p s} \frac{\eta_H P_{tot}}{w_{dep}^2} N_H G_H M_H$$

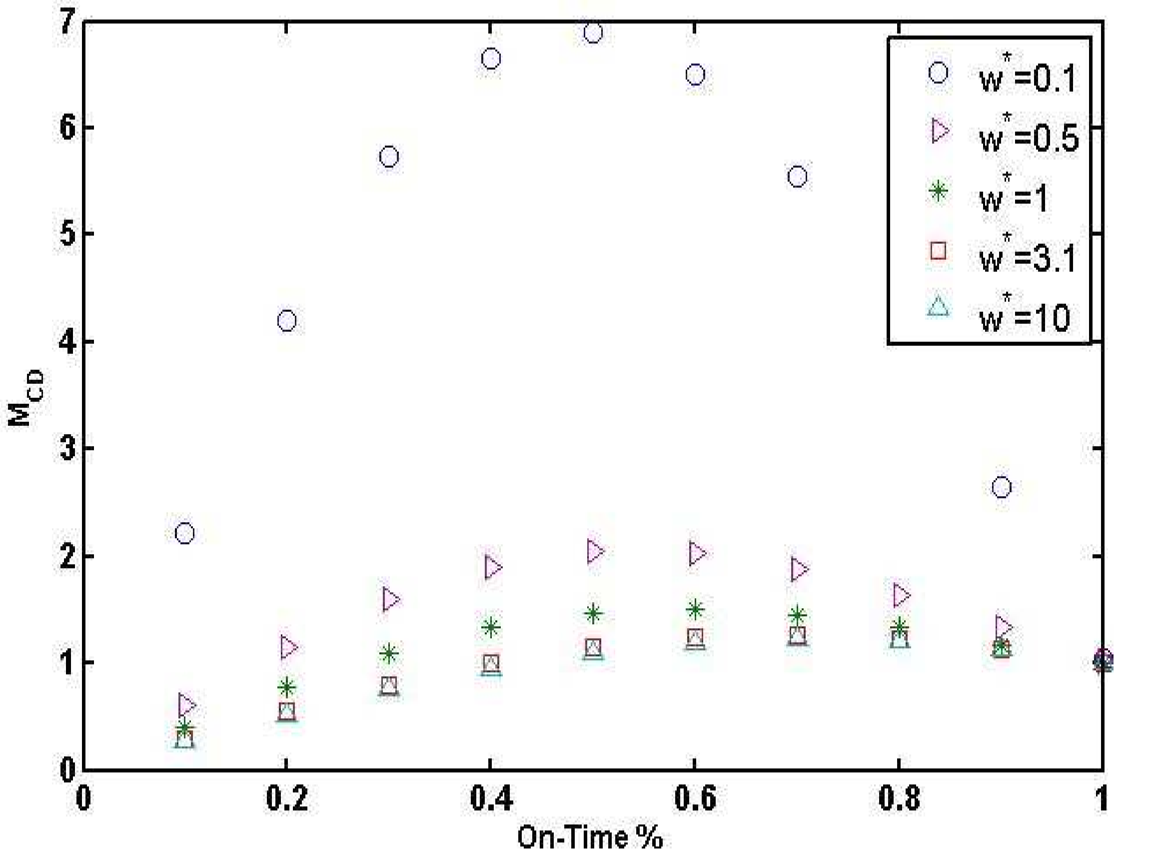
- No G_H=0 crossing, no destabilizing effect;
- At r_N=0.3, G_H is reduced by ~50%;
- Less strict requirement for localization accuracy;



ECCD: Modulating the Power

$$r_s\Delta'_{CD} = \frac{32\mu_0 r_s}{B_p s}\frac{P\eta_{CD}}{w^2_{dep}} N_{CD} G_{CD} M_{CD}$$

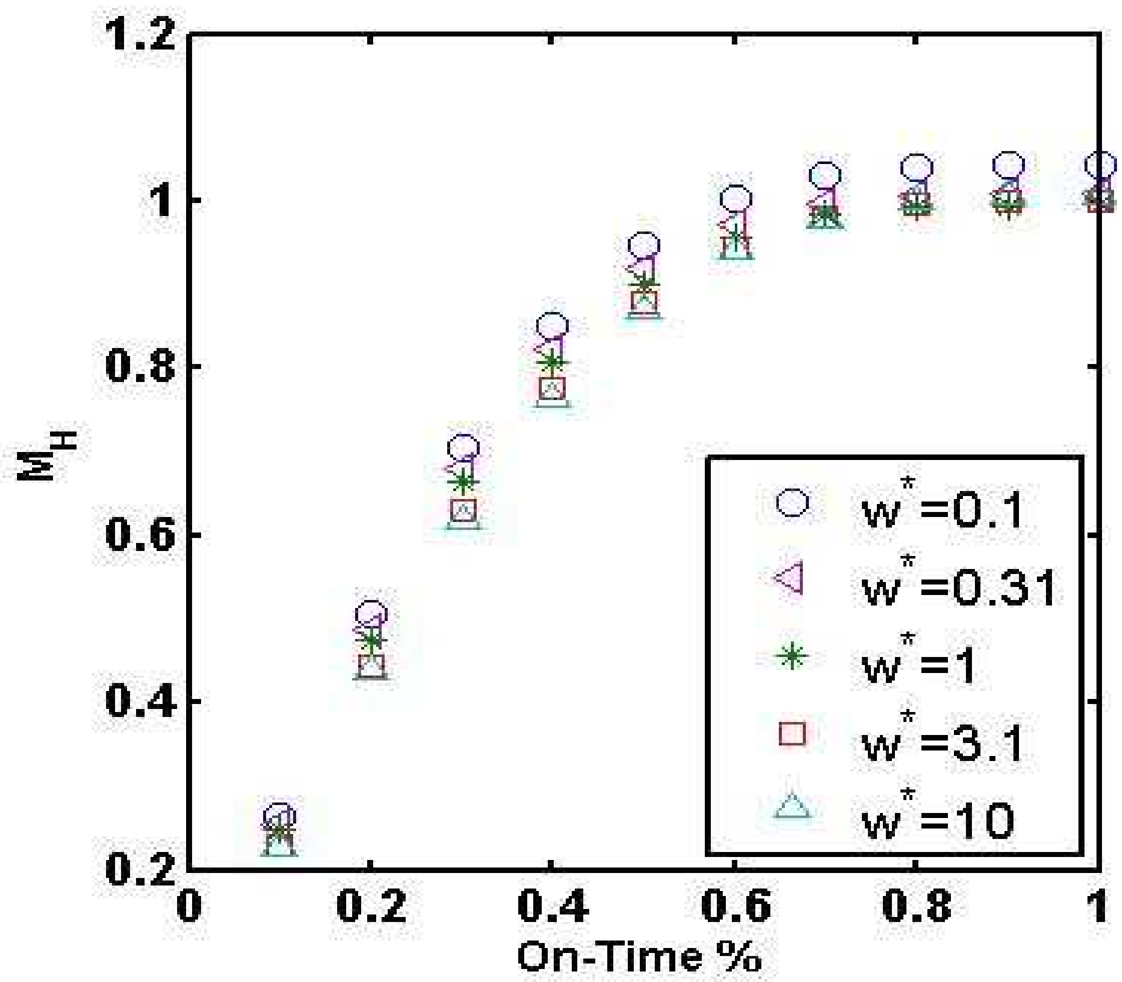
- P_{tot} is the total power in case of CW.
- M_{CD} is optimized at 50% on-time for $w^*<1$, at ~70% for $w^*>1$;



ECRH: Modulating the Power

$$r_s \Delta'_H = \frac{32\mu_0 r_s}{B_p s} \frac{\eta_H P_{tot}}{w_{dep}^2} N_H G_H M_H$$

- Modulation doesn’t enhance ECRH geometrical efficiency;
- At 50% on-time the loss is still negligible, around 10%



ECCD vs. ECRH: The Power Efficiency

$$r_s\Delta'_{H,CD} = \frac{32\mu_0 r_s}{B_p s}\frac{P\eta_{H,CD}}{w_{dep}^2}F_{H,CD}(w^*, r_s - r_{dep}, D)$$

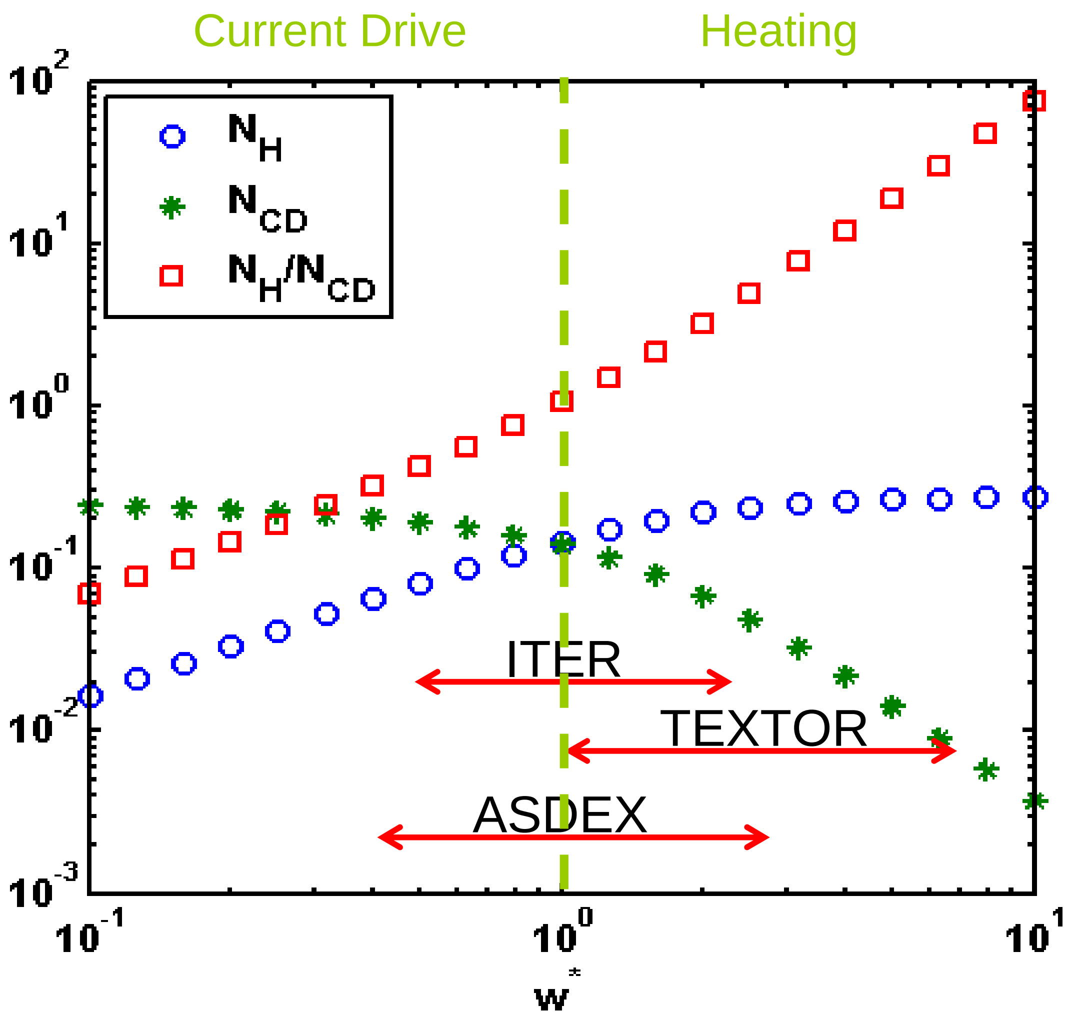
- For w* = 1, $F_{CD} \sim F_H$, so that $r_s\Delta'_{H,CD} \propto \eta_{H,CD}$

$$\eta_H = \frac{3\, w_{dep}^{\;2}}{8\pi\; R\; n_e k_B \chi}\frac{j_s}{T_s} \qquad \eta_{CD} = \frac{I_{CD}}{P}$$

- ”η“ is the efficiency with which the power generates a current perturbation either inductively, through perturbation of a temperature, or non-inductively, by direct current drive.

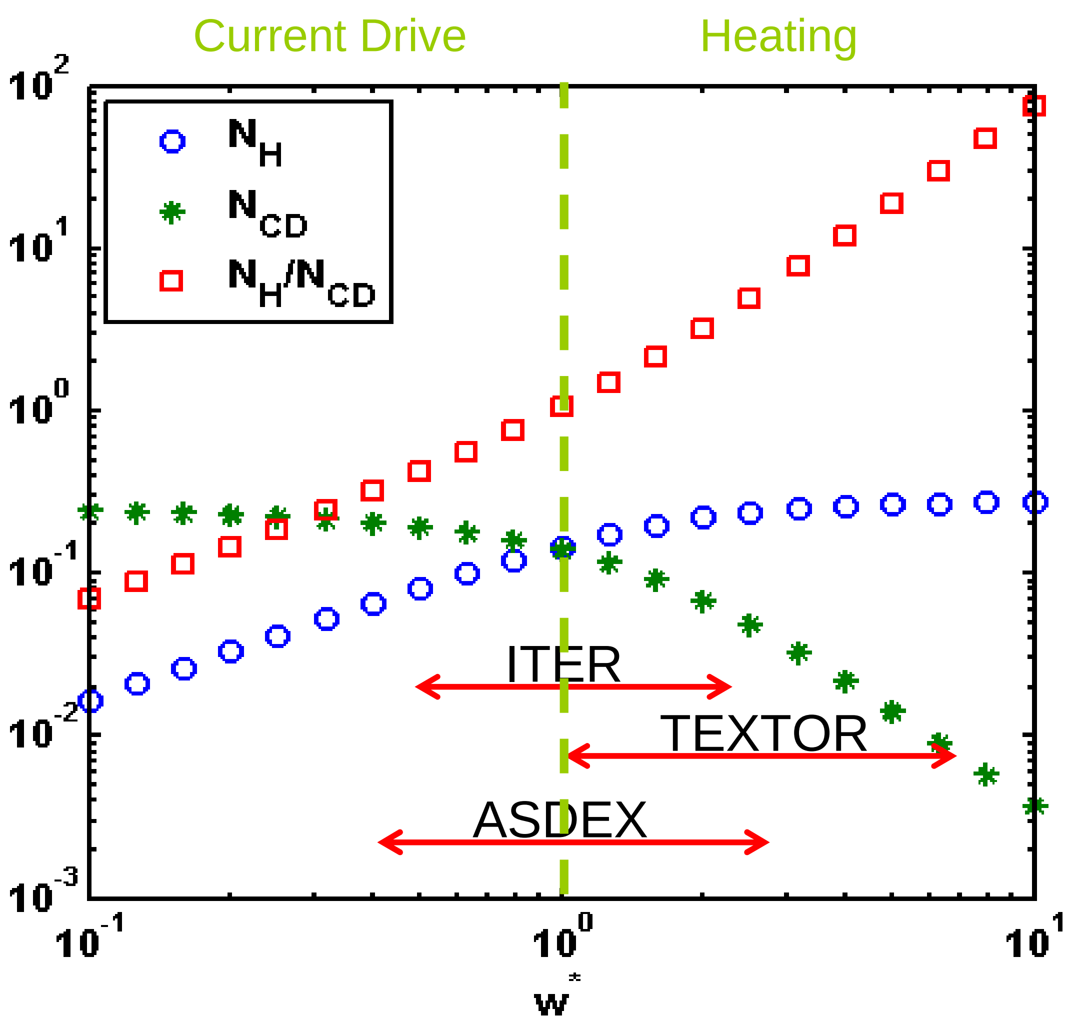
[kA]/[MW]	η_{CD}	η_H
TEXTOR	2.5	2.8
ASDEX	4 - 6	5 - 9
ITER	5.7	0.4

ECCD Vs ECRH: a geometrical comparison



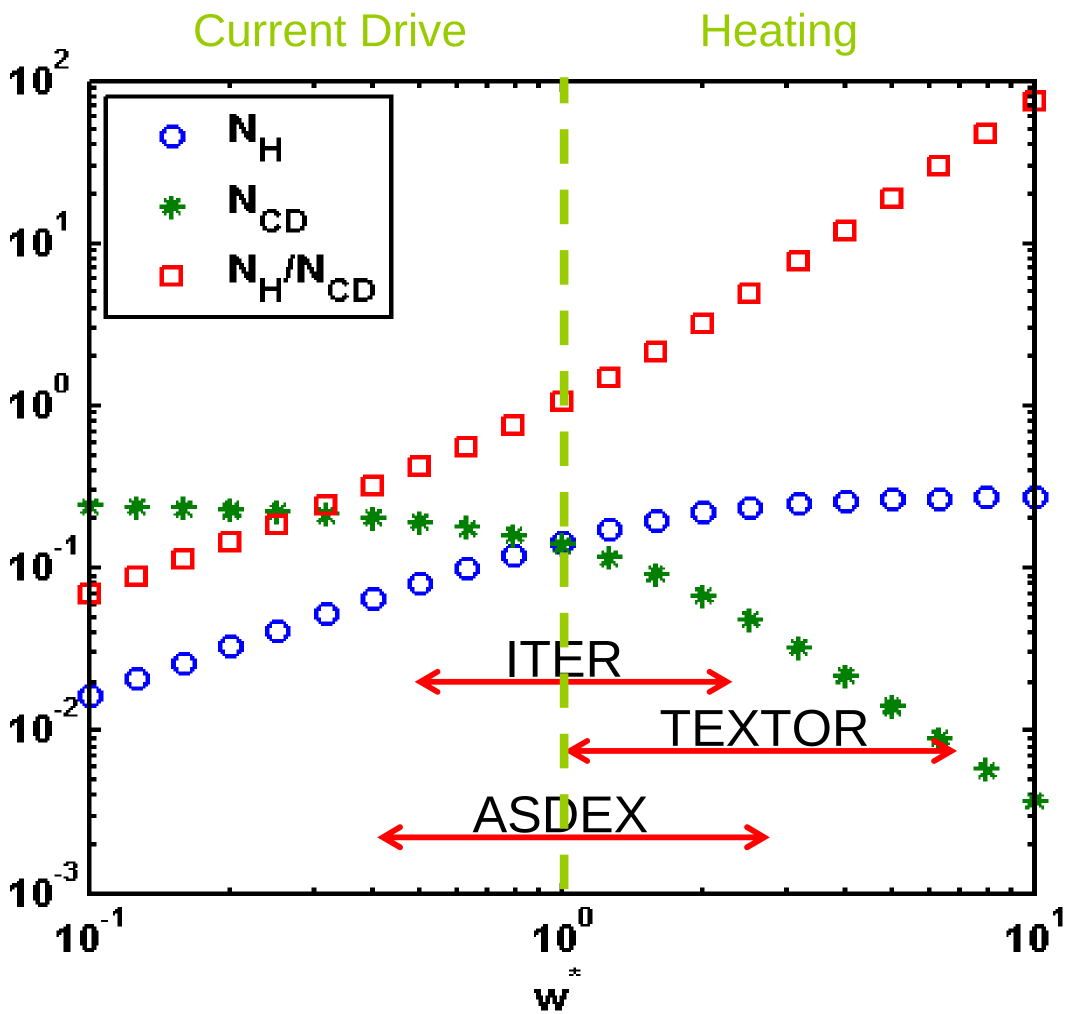
- At w* =1, $F_{CD}=F_H$;
- N_{CD} is decreasing quadratically for w>>w* while N_H is decreasing linearly at w<<w* ;
- Modulation is mostly relevant in the region where current drive is dominant.

ECCD Vs ECRH: a geometrical comparison



- At w* =1, $F_{CD}=F_H$;
- N_{CD} is decreasing quadratically for w>>w* while N_H is decreasing linearly for w<<w* ;
- Modulation is mostly relevant in the region where current drive is dominant.

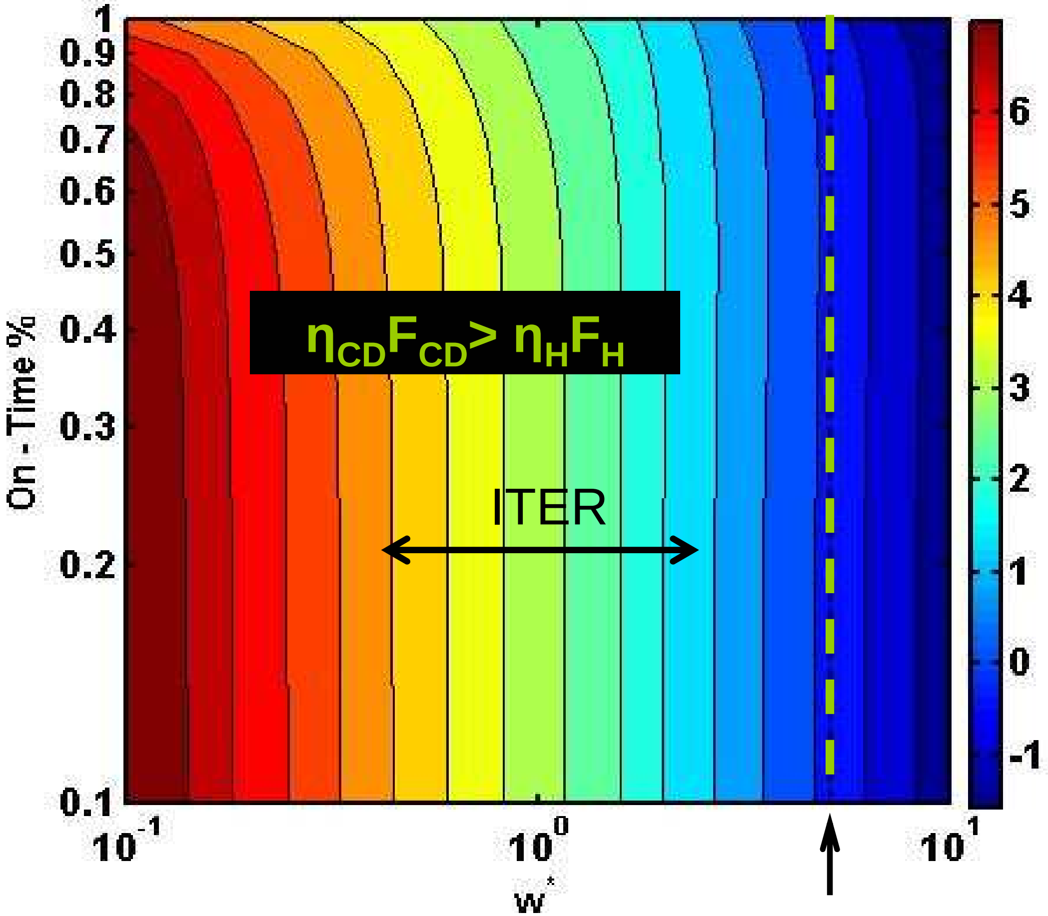
ECCD Vs ECRH: a geometrical comparison



- At w* =1, $F_{CD}=F_H$;
- N_{CD} is decreasing quadratically for w>>w* while N_H is decreasing linearly for w<<w* ;
- Modulation is mostly relevant in the region where current drive is dominant.

…and the winner is? The case of ITER

Log($\eta_{CD}F_{CD}$/ $\eta_H F_H$) in ITER, Scenario 2



Log(…)=0

Typical parameters (Front steering):

P (MW)	I_{CD} (MA)	w_{dep} (cm)	η_{CD}	η_H
13.3	0.76	4.9	5.74	0.4

- For a saturated 3/2 island (about 12.5cm), ECCD appears ~ 4.5 times more efficient than ECRH;

JÜLICH FORSCHUNGSZENTRUM

Conclusions and Outlooks

- High accuracy required for ECCD localization:
  - At $\mathbf{r_{dep}}$ **~0.3 max(w,$\mathbf{w_{dep}}$)** G_{CD} is reduced by **~60%** while
  - G_H only by **~50%**;

- Power modulation enhances mainly ECCD efficiency. Best performances are found:
  - At **50%** on-time for **w*<1**,
  - At **70%** on-time for **w*>1**;

- The relative merit of ECCD and ECRH depends on $\eta_{H,CD}F_{H,CD}$;

- ECRH seems to become dominant at w/w_{dep} >>1;

Coming Next:

- D. De Lazzari, E. Westerhof, "*On the Merits of Heating and Current Drive for tearing modes stabilization*", to be submitted to Nucl. Fusion;
- Comparison with experimental data.

Conclusions and Outlooks

- High accuracy required for ECCD localization:
  - At $\mathbf{r_{dep}}$ **~0.3 max(w,w$_{\mathbf{dep}}$)** G_{CD} is reduced by **~60%** while
  - G_H only by **~50%**;

- Power modulation enhances mainly ECCD efficiency. Best performances are found:
  - At **50%** on-time for **w*<1**,
  - At **70%** on-time for **w*>1**;

- The relative merit of ECCD and ECRH depends on $\eta_{H,CD}F_{H,CD}$;

- ECRH seems to become dominant at w/w_{dep} >>1;

Coming Next:

- D. De Lazzari, E. Westerhof, "*On the Merits of Heating and Current Drive for tearing modes stabilization*", to be submitted to Nucl. Fusion;
- Comparison with experimental data.

Conclusions and Outlooks

- High accuracy required for ECCD localization:
  - At $\mathbf{r_{dep}}$ **~0.3 max(w,$\mathbf{w_{dep}}$)** G_{CD} is reduced by **~60%** while
  - G_H only by **~50%**;

- Power modulation enhances mainly ECCD efficiency. Best performances are found:
  - At **50%** on-time for **w*<1**,
  - At **70%** on-time for **w*>1**;

- The relative merit of ECCD and ECRH depends on $\eta_{H,CD}F_{H,CD}$;

- ECRH seems to become dominant at w/w_{dep} >>1;

Coming Next:

- D. De Lazzari, E. Westerhof, "*On the Merits of Heating and Current Drive for tearing modes stabilization*", to be submitted to Nucl. Fusion;
- Comparison with experimental data.

JÜLICH FORSCHUNGSZENTRUM

Conclusions and Outlooks

- High accuracy required for ECCD localization:
  - At **r_{dep} ~0.3 max(w,w_{dep})** G_{CD} is reduced by **~60%** while
  - G_H only by **~50%**;

- Power modulation enhances mainly ECCD efficiency. Best performances are found:
  - At **50%** on-time for **w*<1**,
  - At **70%** on-time for **w*>1**;

- The relative merit of ECCD and ECRH depends on $\eta_{H,CD}F_{H,CD}$;

- ECRH seems to become dominant at w/w_{dep} >>1;

Coming Next:

- D. De Lazzari, E. Westerhof, "*On the Merits of Heating and Current Drive for tearing modes stabilization*", to be submitted to Nucl. Fusion;
- Comparison with experimental data.

Conclusions and Outlooks

- High accuracy required for ECCD localization:
  - At **r_{dep} ~0.3 max(w,w_{dep})** G_{CD} is reduced by **~60%** while
  - G_H only by **~50%**;

- Power modulation enhances mainly ECCD efficiency. Best performances are found:
  - At **50%** on-time for **w*<1**,
  - At **70%** on-time for **w*>1**;

- The relative merit of ECCD and ECRH depends on $\eta_{H,CD}F_{H,CD}$;

- ECRH seems to become dominant at w/w_{dep} >>1;

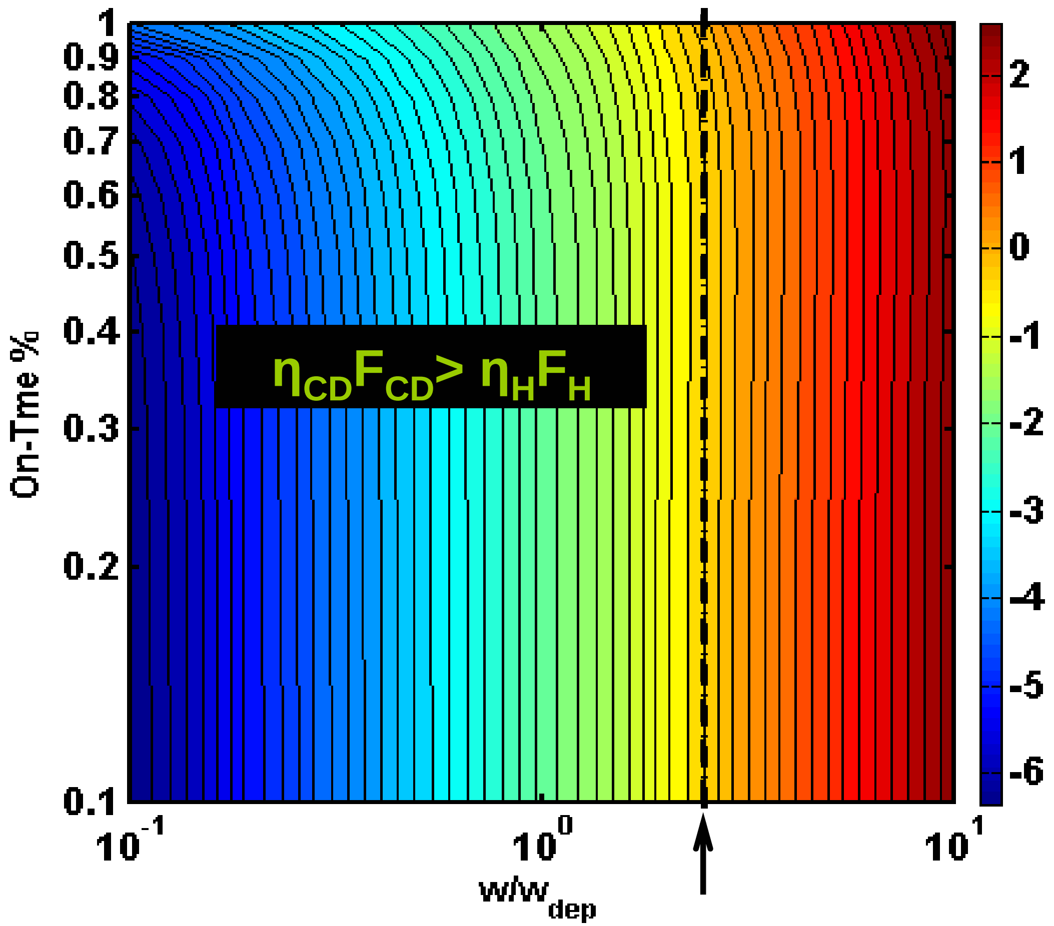
Coming Next:

- D. De Lazzari, E. Westerhof, "*On the Merits of Heating and Current Drive for tearing modes stabilization*", to be submitted to Nucl. Fusion;
- Comparison with experimental data.

THANK YOU FOR YOUR ATTENTION!

…and the winner is? The case of ITER

$Log(\eta_H F_H / \eta_{CD} F_{CD})$ in ITER, Scenario 2



Log(…)=0

Typical parameters (Remote steering):

P (MW)	I_{CD} (MA)	w_{dep} (cm)	η_{CD}	η_H
15	0.12	11.2	8.4	1.9

- For a saturated 3/2 island (about 12.5cm), ECCD appears more efficient;

ECH: Brief Theoretical Description

- T(Ω) constant over the magnetic flux surface;
- Convection effects neglected;
- Constant diffusion coefficient;
- Steady state conditions.

Plasma diffusion equation:

$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle (\nabla V)^2 \right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V} \right)$$

ECH: Brief Theoretical Description

- T(Ω) constant over the magnetic flux surface;
- Convection effects neglected;
- Constant diffusion coefficient;
- Steady state conditions.

$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle (\nabla V)^2 \right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V}\right)$$

$$T_e = T_{sep} - \frac{P_{tot} w}{n_e k \chi_\perp 8\pi^2 R r_s} \int_\Omega^1 d\Omega \langle \delta T_e \rangle$$

ECH: Brief Theoretical Description

- T(Ω) constant over the magnetic flux surface;
- Convection effects neglected;
- Constant diffusion coefficient;
- Steady state conditions.

$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle (\nabla V)^2 \right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V}\right)$$

$$T_e = T_{sep} - \frac{P_{tot} w}{n_e k \chi_\perp 8\pi^2 R r_s} \int_{\Omega}^{1} d\Omega \, \langle \delta T_e \rangle$$

$$r_s \Delta'_H = \frac{2\mu_0 R}{C w^2} \frac{J_{sep}}{T_{sep}^{3/2}} \int_{-1}^{+1} d\Omega \, r_s T_e^{3/2} \oint d\xi \frac{w}{4\sqrt{2}} \frac{\cos(m\xi)}{\sqrt{\Omega + cos(m\xi)}}$$

ECH: Brief Theoretical Description

- $T(\Omega)$ constant over the magnetic flux surface;
- Convection effects neglected;
- Constant diffusion coefficient;
- Steady state conditions.

$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle (\nabla V)^2 \right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V}\right)$$

$$T_e = T_{sep} - \frac{P_{tot} w}{n_e k \chi_\perp 8\pi^2 R r_s} \int_\Omega^1 d\Omega \langle \delta T_e \rangle$$

$$r_s \Delta'_H = \frac{2\mu_0 R}{C w^2} \frac{J_{sep}}{T_{sep}^{3/2}} \int_{-1}^{+1} d\Omega\, r_s T_e^{3/2} \oint d\xi \frac{w}{4\sqrt{2}} \frac{\cos(m\xi)}{\sqrt{\Omega + \cos(m\xi)}}$$

$$\approx \frac{32\mu_0 r_s}{B_p s} \frac{\eta_H P_{tot}}{w_{dep}^2} F_H\left(w^*, r_{dep} - r_s, D\right)$$

$$F_H \approx N_H\left(w^*, r_{dep} = r_s\right) G_H\left(w^*, R_{dep} - r_s\right) M_H(w^*, D)$$

ECH: Brief Theoretical Description

- T(Ω) constant over the magnetic flux surface;
- Convection effects neglected;
- Constant diffusion coefficient;
- Steady state conditions.

$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle (\nabla V)^2 \right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V}\right)$$

$$T_e = T_{sep} - \frac{P_{tot} w}{n_e k \chi_\perp 8\pi^2 R r_s} \int_\Omega^1 d\Omega \left\langle \delta T_e \right\rangle$$

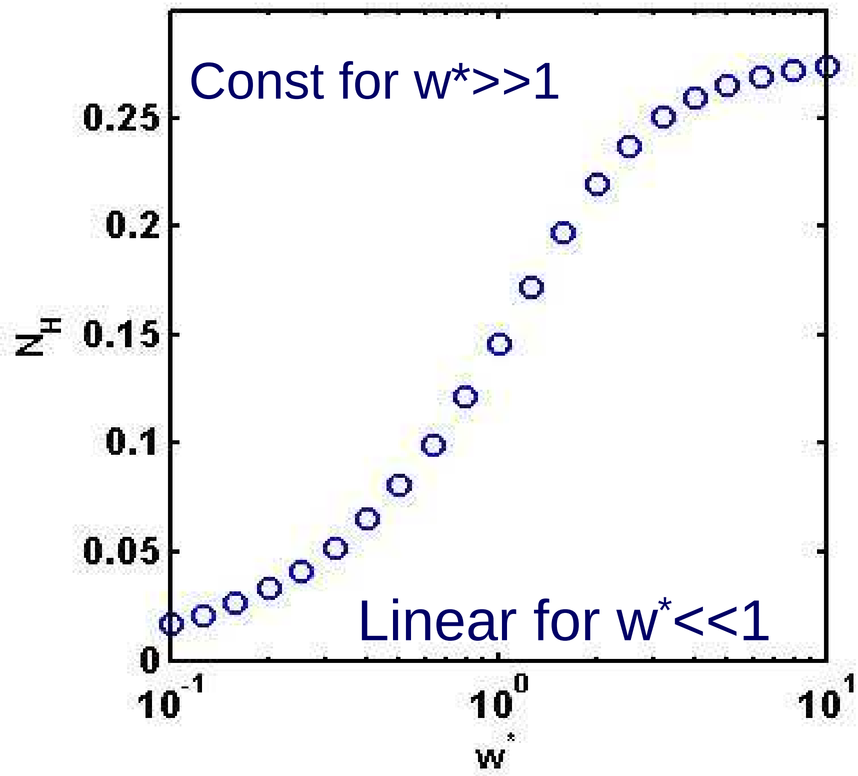
$$r_s \Delta'_H = \frac{2\mu_0 R}{C w^2} \frac{J_{sep}}{T_{sep}^{3/2}} \int_{-1}^{+1} d\Omega \, r_s T_e^{3/2} \oint d\xi \frac{w}{4\sqrt{2}} \frac{\cos(m\xi)}{\sqrt{\Omega + \cos(m\xi)}}$$

$$\approx \frac{32\mu_0 r_s}{B_p s} \frac{\eta_H P_{tot}}{w_{dep}^2} F_H\left(w^*, r_{dep} - r_s, D\right)$$

$$F_H \approx N_H\left(w^*, r_{dep} = r_s\right) G_H\left(w^*, r_{dep} - r_s\right) M_H(w^*, D)$$

ECH: Brief Theoretical Description

$$N_H(w^*) = \frac{0.27w^{*2} + 0.39w^*}{w^{*2} + w^* + 2.5}$$



$$S(\Omega) = -\frac{\partial}{\partial V}\left(\left\langle(\nabla V)^2\right\rangle n_e k \chi_\perp \frac{\partial T}{\partial V}\right)$$

$$T_e = T_{sep} - \frac{P_{tot} w}{n_e k \chi_\perp 8\pi^2 R r_s} \int_\Omega^1 d\Omega \langle \delta T_e \rangle$$

$$r_s \Delta'_H = \frac{2\mu_0 R}{C w^2} \frac{J_{sep}}{T_{sep}^{3/2}} \int_{-1}^{+1} d\Omega \, r_s T_e^{3/2} \oint d\xi \frac{w}{4\sqrt{2}} \frac{\cos(m\xi)}{\sqrt{\Omega + \cos(m\xi)}}$$

$$\approx \frac{32\mu_0 r_s}{B_p s} \frac{\eta_H P_{tot}}{w_{dep}^2} F_H\left(w^*, r_{dep} - r_s, D\right)$$

$$F_H \approx N_H\left(w^*, r_{dep} = r_s\right) G_H\left(w^*, R_{dep} - r_s\right) M_H(w^*, D)$$

Questions & Details?

- Modulation function: $H(\xi;D,\phi) = H(|\cos(m\xi/2+\phi) - \cos(D\pi/2)|)$